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Reconciling Different Forms of Ecological Integrity to Aid the Kunming-Montreal Global Biodiversity Framework

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ABSTRACT

With the Kunming-Montreal Global Biodiversity Framework (GBF), the international community has committed to retaining ecosystems of high ecological integrity. Monitoring progress toward this target requires the identification of suitable indicators, but these are not universally recognized. In this study, we analyze available global maps of terrestrial ecological integrity and evaluate their representation of different dimensions of integrity (structure, composition, and function). Although 73% of terrestrial surface holds conservation value according to at least one map, less than 1% of land attains high integrity according to all of them. Solely relying on one indicator map risks overlooking the integrity value of at least 41 million km^2 of land, with some key areas for biodiversity conservation inadequately represented by these indicators of integrity. However, when used in combination, complementary dimensions of integrity help identify an area covering 41.1% of the terrestrial surface, two-thirds requiring urgent conservation action. The synergistic use of existing measures offers considerable potential to guide the implementation of Target 1 of the GBF while supporting more equitable conservation paradigms. Developing robust indicators and understanding the link among different ecological dimensions is essential to protect ecosystems of high ecological integrity in the long term.

1 | Introduction

The Kunming-Montreal Biodiversity Framework, also known as the post-2020 Global Biodiversity Framework (GBF), was adopted at the COP 15 of the Convention on Biological Diversity (CBD) in 2022 to catalyze global conservation efforts and reverse the ongoing decline of biodiversity (CBD/COP/15/L25 2022). Among many new concepts formalized in the post-2020 GBF, the conservation of ecosystems of high ecological integrity (as articulated in Target 1) plays a central role in achieving conservation objectives, highlighting the importance of preventing ecosystem degradation and not just reacting to it (Mokany et al. 2020).

Ecological integrity, as defined by the CBD, refers to an ecosystem's capacity to maintain its structure, composition, and functioning within a natural range of variability over time (CBD/SBSTTA/24/3/Add.2 2021). The concept of integrity relates to the properties of an ecosystem, and it represents a holistic assessment of ecosystems' health and resilience (Hansen et al. 2021). Importantly, integrity is best understood as a gradient,

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rather than a binary characteristic, spanning from urban or industrialized areas to intact regions (Carter et al. 2019; Watson et al. 2016). However, a demarcation line is often drawn when referring to ecosystems in relation to their intactness (Hill et al. 2022; Nicholson et al. 2021). Intactness is considered the quality of a natural area that has not faced industrial-scale exploitation (Allan et al. 2022). Large intact areas with no large-scale impacts are now the only places that contain mixes of species at near-natural levels of abundance (Plumptre et al. 2021) and provide increasingly important refuges for species that are declining in landscapes dominated by intense human activities (Di Marco et al. 2019). Thereby, when specific data are lacking or inaccessible, intactness is used as a proxy of overall ecological integrity (Blumetto et al. 2019; Newbold et al. 2016). The definition of a threshold level, in these cases, allows the integrity of an ecosystem to be framed in discrete or binary categories, which is essential for analyzing environmental threats, monitoring ecological trends, and guiding conservation actions (Allan, Venter, and Watson 2017).

However, the concept of integrity is extremely nuanced, and several initiatives have attempted to map the ecological integrity of global ecosystems, applying different philosophies (Pérez-Hämmerle et al. 2021) and methodologies (Nicholson et al. 2020). Differences in methodologies for mapping areas of high ecological integrity challenge a shared comprehension of the conservation status of global ecosystems, potentially undermining the effective implementation of conservation measures (Venter et al. 2017; Visconti et al. 2019). As time to achieve Target 1 of the post-2020 GBF is rapidly running out, there is an urgent need for understanding how multiple metrics connect to each other and to the three dimensions of ecosystem integrity (structural, compositional, and functional). Although the indicators for Target 1 exist, such as the Red List of Ecosystems and the extent of natural ecosystems (CBD/COP/DEC/15/5 2022), they are not fully representative of all existing methodologies for mapping integrity, falling short of capturing the complexity of ecological integrity. Although ecological integrity is a multifaceted concept (see next section), most existing indicators practically focus only on one dimension of integrity. We therefore focus our analyses of “areas of high ecological integrity” on the individual components of integrity, without implying that all components are represented at once. With the objective of enhancing the monitoring and effective implementation of Target 1 within the post-2020 GBF, we evaluated the diverse frameworks and methods utilized to map terrestrial ecosystems of high ecological integrity in recent years. We conducted a systematic literature review and compared the approaches adopted to assess ecological integrity at the global scale. All maps of integrity we analyzed rely on measures of anthropogenic pressure to some extent (Table 1). We then exported all the available integrity maps that had been created and analyzed their spatial distribution. To ensure the comparability of the selected maps, we converted values of continuous maps into binary representations, distinguishing areas of “high integrity” from the rest. In this process, we adhered to the guidelines provided by their authors whenever such guidance was available. In cases where thresholds were absent, we established arbitrary thresholds and tested them through a sensitivity analysis (Appendix S1). On the basis of the results of the spatial analysis, we discuss the conservation implications of available approaches to map ecological integrity. We proceed by explaining the connections among different approaches, interpreting their differences based on both their divergences and potential synergies. We conclude by providing recommendations for the monitoring and implementation of Target 1.

2 | Multiple Dimensions of Ecological Integrity

The concept of ecological integrity has evolved over the past three decades, partly following the changing perspective of biodiversity conservation itself (Mace 2014). Initial attempts to map ecological integrity focused on anthropogenic pressures only, embracing the “nature despite people” narrative. However, in recent years, there has been a growing concern for developing approaches that allow for a more holistic consideration of ecosystems (Table 1). Shifting narratives have significantly influenced the development of maps depicting integrity, which can be broadly categorized into three approaches: structural, compositional, and functional (Figure 1).

2.1 | Structure-Oriented Approaches

Structure-oriented approaches focus on the physical organization and pattern of ecosystems, including the spatial arrangement of biotic and abiotic elements. Within this approach, ecological integrity is considered a structural descriptor of landscapes, reflecting the absence of anthropogenic disturbance (CBD/SBSTTA/24/3/Add.2 2021). Most of the approaches used to map ecological integrity can be associated with this category. The mapping of ecosystem’s structural integrity initially aimed to identify areas that had not been exposed to anthropogenic impacts leading to the conversion of natural habitats (McCloskey and Spalding 1989). This mapping was achieved by using a combination of variables that describe human impact on natural ecosystems at a global scale, such as the presence of human settlements, infrastructures, roads, and population density (Sanderson et al. 2002; Vernier et al. 2022). Because one of the aspects of intactness mapping was the identification of ecosystems that preserve their preindustrial status, the early focus of intactness mapping was on separating undisturbed (or “wilderness”) areas from the rest (Hannah, Carr, and Lankerani 1995). Subsequent approaches also involved establishing minimum area sizes for wilderness or prioritizing the largest contiguous areas among those retaining lower levels of anthropogenic impact (Mittermeier et al. 2003). With the advancement of satellite technology and remote sensing, it has become increasingly possible to collect high-resolution data on additional anthropogenic drivers of land-use change, such as cropland and urbanization (Kennedy et al. 2019). This “new generation” of maps incorporates satellite data to measure the cumulative effect of certain anthropogenic drivers with increasing accuracy. These approaches have been deployed at both coarse resolutions, for example, biome-level (Allan et al. 2017) and fine resolutions (Jacobson et al. 2019). An additional step involves integrating measures of connectivity to account for the effect of fragmentation on biome ecosystem structure (Beyer et al. 2020; Hill et al. 2022). A slightly different approach is that of the Anthromes database, which aims to track how human influence has reshaped ecosystems and how biodiversity has adapted to it. In this case, intact areas are identified through cluster analysis based on the spatial patterns of anthropogenic drivers of environmental change (Ellis, Beusen, and Goldewijk 2020).

TABLE 1 | Overview of the existing global maps of high ecological integrity.

Map name	Authors	Definition of high ecological integrity	Integrity dimension	Methodology	Year	Availability
Wilderness	McCloskey and Spalding (1989)	Areas where nature predominates	Structure—it assesses human influence	Gradually eliminate all areas showing roads, settlements, buildings, airports, railroads, pipelines, powerlines, canals, causeways, aqueducts, major mines, dams and reservoirs, and oil wells, and select just those >400,000 ha	1988	Outdated
Undisturbed habitats	Hannah, Carr, and Lankerani (1995)	Undisturbed area retaining primary vegetation and low human population density	Structure—it relates to the quality of an area of being undisturbed by human drivers	Measure the percentage of area where there is a record of primary vegetation and where there is no evidence of disturbance combined with very low human population density (habitat index)	1980–1990	Outdated
Last of wild	Sanderson et al. (2002)	Wilder, or least influenced, areas in each biome	Structure—it identifies the 10 largest contiguous areas between those scoring the lowest human influence	Identify the 10 largest contiguous areas within the 10% wildest areas (scoring the lowest value for the HII) in each biome realm based on nine variables that measure population density, land transformation, accessibility, and electrical power infrastructure	2001	Outdated
Wilderness areas	Mittermeier et al. (2003)	Large areas of unmodified or slightly modified land retaining their natural character, influence, and condition	Structure—it identifies contiguous, intact areas using a combination of indicators of human influence	Identify contiguous areas >10,000 km^2 with human population density <5 people/km^2 and retaining at least 70% of its historical habitat extent (500 years). The selection of the wilderness areas also relies on a literature search and expert opinion	2000	Outdated
Biodiversity Intactness Index (BII)	Newbold et al. (2016)	Natural and undisturbed ecosystems retaining 10% of their species abundance and 20% of their species richness	Composition—it is a measure of species' abundance and richness relative to abundance in an undisturbed habitat	The response of biodiversity (species abundance and richness) to stressor variables (land use, land use intensity, human population density, and distance to the nearest road) is modeled as an output of PREDICTS biodiversity model and used to infer the degree of the biodiversity intactness of each site, considering its degree of disturbance and comparing it to an undisturbed baseline	2000–2005	Open source

(Continues)

TABLE 1 | (Continued)

Map name	Authors	Definition of high ecological integrity	Integrity dimension	Methodology	Year	Availability
Last of wild *named "**Intact areas**" in Allan et al. (2022)	Allan et al. (2017)	Areas free of industrial-scale activities and other human pressures that result in significant biophysical disturbance	Structure—it identifies areas free of human pressures that result in significant degradation of the ecosystem structure	Measures the Human Footprint Index (HFI) for each ecoregion and selects those retaining a contiguous area with HFI < 1. The "last of wild" are the 10 largest contiguous areas in each bio-realm with an area >10,000 km^2. For each cell, the HFI accounts for built environments, population density, night-time light, croplands, pasture land, roads, railways, and navigable waters	2009	Open source
Very low impact areas (VLIA)	Jacobson et al. (2019)	Landscapes that have low human density and impacts, not primarily managed for human needs	Structure—it identifies areas of minimum human impact	Identifies cells of minimal anthropogenic impact based on a combination of human population, livestock density, forest change, land cover, and nighttime lights and absence of roads	2015	Open source
Low modified areas	Kennedy et al. (2019)	Natural areas relatively free from human alteration	Structure—it measures the cumulative impact of physical drivers of environmental modification	Relies on a human modification model (the Global Human Modification Index—HMI) to measure the spatial extent, intensity, and co-occurrence of 13 anthropogenic stressors (population density, built-up areas, cropland, livestock, major roads, minor roads, two tracks, railroads, mining, oil wells, wind turbines, powerlines, and nighttime lights)	2016	Open source
Wildlands	Ellis, Beusen, and Goldewijk (2020)	Uninhabited and unused landscapes	Structure—intactness relates to anthropogenic drivers of environmental degradation	Relies on the Anthromes database, which applies a cluster analysis to identify the most significant spatial patterns of human populations, land use, and vegetation cover to identify categories of anthropogenic biomes	2015	Open source

(Continues)

TABLE 1 | (Continued)

Map name	Authors	Definition of high ecological integrity	Integrity dimension	Methodology	Year	Availability
Biodiversity Habitat Index	Harwood et al. (2022)	(Not explicated)	Composition—it estimates the level of species diversity (beta diversity) expected to be retained within any given spatial unit as a function of the unit's area, connectivity, and integrity of natural ecosystems across it	It is calculated using CSIRO's BILBI biodiversity modeling infrastructure and the global biodiversity information facility data. The indicator is developed in two steps. First, a correlative model is adopted to determine the spatial variation in species composition as a function of environmental variables (e.g., climate, terrain, and soil). Then, this information is used in combination with variables that describe anthropogenic pressure in each site to determine the real contribution of the site to maintain similar biological composition to others. Habitat condition is calculated from downscaled land use harmonization surfaces combined with coefficients from the PREDICTS database. The model generates spatial biodiversity data for each WWF biome/realm combination, and resulting values can be aggregated across sites to determine the regional condition of any given species assemblage at different scales	2015; 2020	Open source
Ecoregion intactness	Beyer et al. (2020)	Unmodified landscape or habitat	Structure—is a measure of the combined impact of habitat loss, fragmentation, and degradation, arising from anthropogenic disturbance	Assess the intactness value of each ecoregion by applying a metric that measures the value of each cell in relation to its HFI value and the HFI of the surrounding landscape. The metric also accounts for the habitat patch size, fragmentation, and connectivity	2009	Open source
Contextual intactness	Mokany et al. (2020)	Areas with the highest habitat condition where all other biologically similar locations are in a worse condition	Composition—combines data on changes in species composition and anthropogenic drivers of change	Combines the HFI and BILBI for terrestrial vertebrates, invertebrates, and plants to measure the condition of the habitats that would be expected to host a similar assemblage of species. The contextual intactness of an area is given by the sum of assemblage similarities to the areas with a higher HFI divided by the total sum of assemblage similarities	2013	Open source

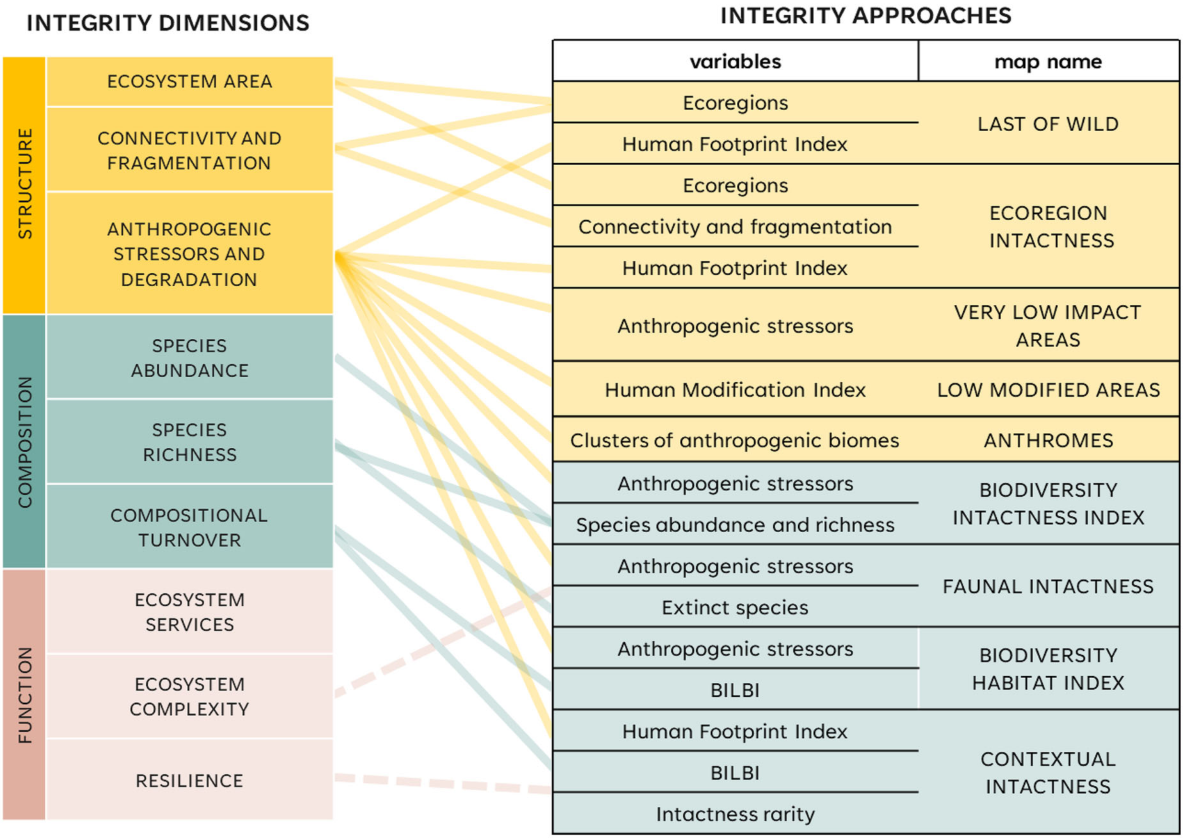
(Continues)

TABLE 1 | (Continued)

Map name	Authors	Definition of high ecological integrity	Integrity dimension	Methodology	Year	Availability
Faunal intactness	Plumptre et al. (2021)	A site where ecological communities preserve the composition and the abundance of their native species and their interactions	Composition—it accounts for species extirpation and extinction due to anthropogenic drivers According to the authors, it also relates to function	Identifies areas with low HFI and assesses where species have been historically extirpated where species densities are low (below functional density) and where this is likely to have been caused by human influence	2018	Open source
Ecosystems' structure integrity	Hill et al. (2022)	Derived from Beyer et al. (2020)	Structure—it is explicitly used as a proxy of ecosystem's structure	Uses the HMI and follows Beyer et al. (2020) with a moving window that compares the quality of a grid cell with that of cells within a 27 km distance from it (i.e., grid cells in a 55 km × 55 km box)		Not available
Ecosystems' composition integrity	Hill et al. (2022)	Derived from Newbold et al. (2016)	Composition—it evaluates changes in species abundance and community composition relative to natural conditions	This index builds on the BII framework developed by Newbold et al. (2016). The updated global layer (Hill et al. 2018) refines and extends the original BII metrics		Not available
Ecosystems' functional integrity	Hill et al. (2022)	Minimal human-induced degradation of the net primary productivity	Function—explicitly used as a proxy for ecosystem's function	Net primary productivity (NPP) was measured for each grid cell using environmental variables and trained on mean NPP levels. These natural NPP estimates were then compared with current-day NPP values derived from remote sensing to assess proportional losses in NPP		Not available

Note: Columns are defined as follows: "Map name" refers to the title of each map; "Authors" report the study whereby the map was published; "Definition of high ecological integrity" provides details on the concept of integrity adopted by the authors; "Integrity dimension" specifies the aspect of ecological integrity being evaluated in the map (i.e., structure, composition, or function) alongside the rationale for such classification in this study; "Methodology" offers a detailed description of the methods adopted to identify and classify areas of high ecological integrity; "Year" indicates the year in which the map was published or the data were collected; and "Availability" outlines the current status of the map's relevance and usage.

Abbreviations: BILBI, biogeographic modeling infrastructure for Large-scale biodiversity indicators; HII, Human Influence Index.



variables	map name
Ecoregions	LAST OF WILD
Human Footprint Index	
Ecoregions	ECOREGION INTACTNESS
Connectivity and fragmentation	
Human Footprint Index	
Anthropogenic stressors	VERY LOW IMPACT AREAS
Human Modification Index	LOW MODIFIED AREAS
Clusters of anthropogenic biomes	ANTHROMES
Anthropogenic stressors	BIODIVERSITY INTACTNESS INDEX
Species abundance and richness	
Anthropogenic stressors	FAUNAL INTACTNESS
Extinct species	
Anthropogenic stressors	BIODIVERSITY HABITAT INDEX
BILBI	
Human Footprint Index	CONTEXTUAL INTACTNESS
BILBI	
Intactness rarity	

FIGURE 1 | Relation between integrity dimensions and existing approaches for mapping areas of high ecological integrity. BILBI, biogeographic modeling infrastructure for large-scale biodiversity indicators.

2.2 | Composition-Oriented Approaches

Composition-oriented approaches refer to the biotic constitution of ecosystems and the patterns of species communities and their interactions. Maps representing compositional integrity assess the biological composition of an area relative to what would be expected under minimal or no anthropogenic pressure, explicitly linking these assessments to the influence of human activities. The Biodiversity Intactness Index (BII) is a notable example in this sense (Hill et al. 2018; Newbold et al. 2016). The BII assesses the response of biodiversity to stressor variables such as land use intensity and human population density. As a result, a model is built to predict the degree of biodiversity intactness of each site, considering its degree of disturbance compared to a “pristine” baseline. The BII identifies undisturbed ecosystems that retain at least 90% of their species abundance or 80% of their species richness. Other composition-oriented metrics, instead, focus on parameters of beta-diversity to assess the intactness of the species composition in a region. This is the case of the Biodiversity Habitat Index (BHI), which is an indicator of change in biodiversity composition based on changes in habitat conditions induced by human pressure (Harwood et al. 2022). This model builds on the biogeographic modeling infrastructure for large-scale biodiversity indicators (BILBI; Hoskins et al. 2020) using a modified form of generalized dissimilarity modeling. The resulting values can be aggregated across sites to determine the regional condition of any given species assemblage. The BILBI approach has multiple potential applications and has also been utilized to generate a global map of Contextual Intactness (Mokany et al. 2020). This approach identifies areas with similar biological assemblages to others but with better environmental conditions. Consequently, high contextual intactness represents the best available environmental condition for a given species assemblage relative to regional habitat availability, serving as a tool to identify “islands” of compositional intactness, where species assemblages are preserved but are at high risk. A different attempt to measure composition intactness is the faunal intactness approach (Plumptre et al. 2021). According to this approach, an area is considered intact when its ecological community maintains the composition and the abundance of its native species along with their interactions. Areas characterized by faunal intactness exhibit low human footprint and have no records of species extirpation or decrease in species density resulting from human influence.

2.3 | Functional-Oriented Approaches

Functional-oriented approaches represent the processes and services that guarantee the resilience and the complexity of ecosystems. This dimension strongly relates to the properties of the ecosystems and does not directly consider the levels of anthropogenic pressure (Hansen et al. 2021). Many approaches developed to assess ecological functionality consider changes in primary productivity (Hill et al. 2022), carbon stock (Sims et al. 2019), or other biophysical aspects of ecosystem functioning. Alternative approaches correlate the magnitude of degradation to the risk of ecological collapse (Rowland et al. 2020). Methodologies developed under this realm are less oriented toward the intactness side of the integrity spectrum and more focused on the maintenance of ecosystem functionality and the reduction of ecosystem collapse risk.

3 | Identification of Integrity and Agreement Across Alternative Approaches

We retained nine maps of ecological integrity (Figure S1) that met the following specific criteria: being global, being available for analysis, and having been created or updated within the last 20 years. To ensure comparability in our spatial analysis of the selected maps, we converted values or continuous maps into binary representations, distinguishing areas of "high integrity" from the rest. It is important to note that although ecological integrity is generally mapped on a continuum, applying a threshold was necessary for spatial comparisons. In the process of converting the continuous maps of high ecological integrity to binary, we adhered to the guidelines provided by their authors whenever such guidance was available. Some maps were explicitly designed to provide integrity categories or thresholds, whereas others lacked such explicit criteria (Table S1). In cases where these thresholds were absent, we established arbitrary thresholds and tested them through a sensitivity analysis (Figure S2). Specifically, the "last of wild," "very low impact areas," "Anthromes," and "faunal intactness" maps were presented in categorical formats. In contrast, the "BII," "ecoregion intactness," and "Human Modification Index" were characterized by continuous values. In these latter cases, we extrapolated integrity categories based on the recommendations of the authors. Moreover, the "BHI" and the "Contextual Intactness Index" presented continuous values, but authors did not offer specific recommendations for interpreting their gradients as categories.

We identified five structure-oriented maps and four composition-oriented maps (Appendix S1). Although in many cases maps were presented as general depictions of ecological integrity, we adopted a conservative approach and limited our classification to instances where clear evidence existed of the relationship between a metric and a given dimension of integrity. On the basis of this, we could not retrieve maps of functional integrity at this stage as they are not available at a global scale. This implies that our analysis of "areas of high ecological integrity" is only partial, limited to two of the dimensions of integrity.

We evaluated the coverage of selected maps and assessed the spatial agreement among them by examining their spatial overlap. For this purpose, we generated a composite map illustrating the count of overlapping maps in each pixel and a map depicting the overlap between structure- and composition-oriented approaches (Figure 2). We also considered the redundancy of similar metrics by analyzing the spatial overlap of the two groups of maps depicting the same dimensions of integrity (Figure S3). Although methodologies and thresholds adopted significantly vary and are not comparable, we assumed all maps to have the same weight (Appendix S2). In other words, we deliberately decided to treat all maps as "equals" in defining spatial overlap, even if this assumption can be easily modified as part of a decision-making process where certain approaches, or certain dimensions of integrity, can be assigned a higher weight if desired.

We found that 73% of the world's surface has high values of ecological integrity for at least one dimension of integrity (structural or compositional). Almost half of the Earth's surface has high integrity according to at least two maps, and almost 30% has high ecological integrity according to four maps or more. Less than 1% of the terrestrial surface has high integrity according to all the maps. We found that 40% of the terrestrial surface has both high structural and compositional integrity according to at least one map representing each of these aspects (Appendix S2). These areas hold significant ecological value, exemplified by renowned ecosystems like the Amazon and the Siberian tundra (Dinerstein et al. 2019). The synergistic use of structure- and composition-oriented approaches forms a potent tool for pinpointing crucial areas in the conservation of biological communities that retain high structural integrity. However, almost half of the area of high ecological integrity identified has either high structural or compositional integrity, but not both (Appendix S2). This result underscores the presence of divergences across mapping approaches and emphasizes the need to consider complementary approaches and data when using integrity maps for monitoring area-based conservation strategies (Geldmann et al. 2021).

Our findings also indicate that certain areas and ecosystems deemed important under different conservation frameworks are inadequately represented by existing maps of high ecological integrity. A notable example is the Congo Basin (Figure 2d), where only small patches are considered to have high ecological integrity according to five maps reviewed. Generally, this region is well represented by composition-oriented maps but overlooked by structure-oriented approaches (Figure 2e). Results of this analysis are further discussed in Supporting Information (Appendix S3).

4 | Country-Scale Responsibilities and the Role of Protected Areas

Virtually all countries of the world have some areas of high ecological integrity, according to the analyzed maps (Table S3). All countries with a land area ≥100 km^2 have at least 10% of land that is considered to have high ecological integrity according to one or multiple maps (except for Malta, Moldova, Ireland, and Singapore). Our findings at the country level reveal a widespread distribution of ecological integrity globally, albeit with disparities across economic categories (Figure 3). Notably, developed and emerging economies exhibit a larger proportion of ecological integrity. Similarly, areas of consensus across maps are larger in these regions (Figure 3b). On the other hand, developing and least developed countries displayed a lower agreement in the integrity of their ecosystems, underscoring the necessity to support action through local assessments in these regions. The implementation of area-based conservation measures and spatial planning in these countries should be evidence-based, context-driven, and acknowledge trade-offs between conservation values and socioeconomic drivers (Hirsch et al. 2011). Under both circumstances, these results reflect the need to integrate detailed field information for validation and complement global maps.

When examining the distribution of protected areas, we found that more than 75% of areas of high structural and compositional integrity fall outside the global network of protected areas.

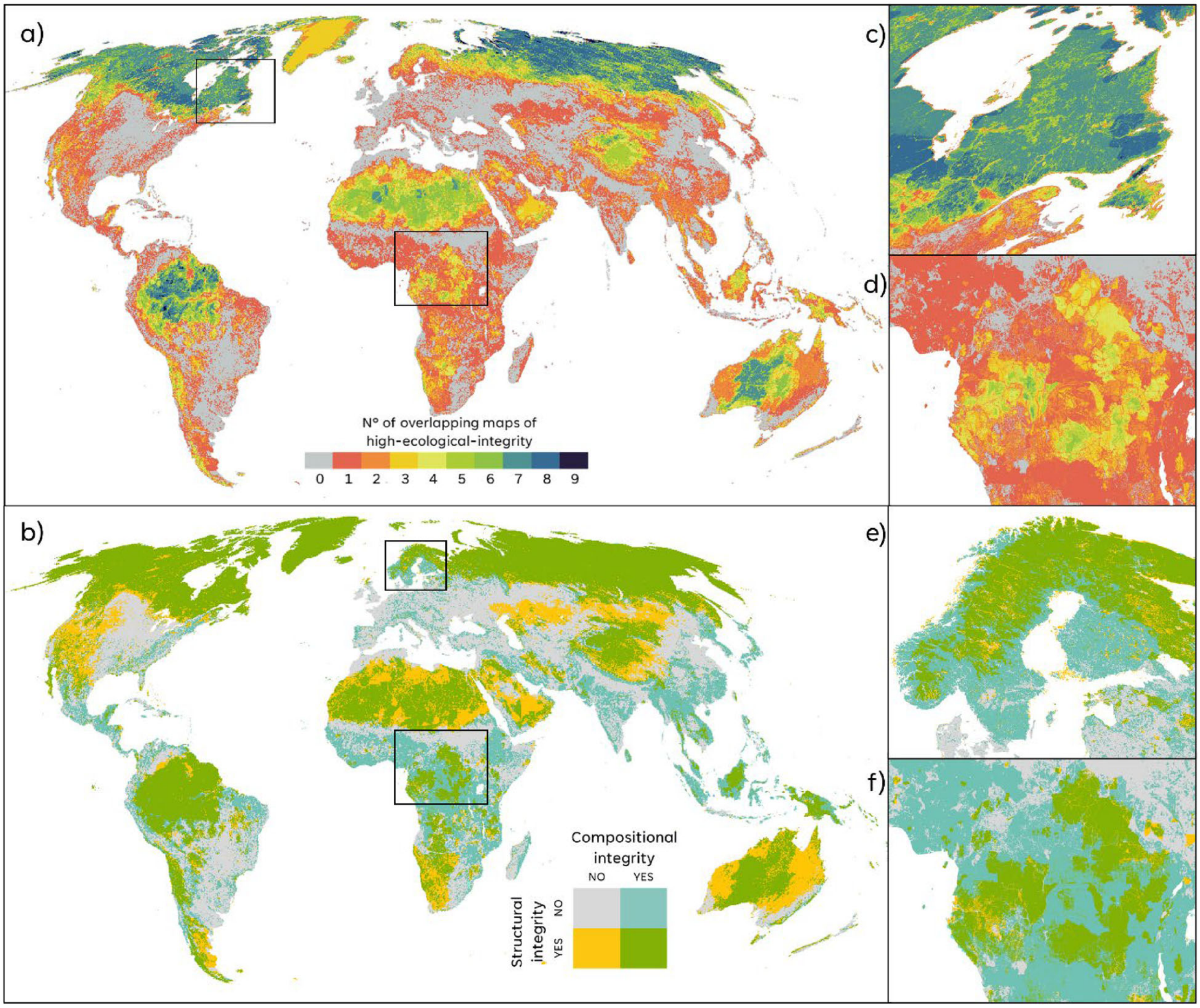


FIGURE 2 | Overlap among nine maps of high ecological integrity illustrating the agreement among the different maps analyzed (a), with zoom on West Canada (c) and the Congo basin (d); and the spatial overlap between structure-oriented (yellow) and composition-oriented (blue) approaches (b), with zoom on Scandinavia (e) and the Congo Basin (f).

Overall, these areas have higher protection (23.2% protected) compared to areas of only high structural integrity (13.8%) or only high compositional integrity (11.6%). However, the post-2020 GBF demands that all areas of high ecological integrity are under biodiversity-inclusive spatial planning. At the same time, the achievement of the 30 × 30 Target demands the rapid expansion of the network of protected areas, with ecosystems of high ecological integrity likely to be prioritized in this process (Visconti et al. 2019). In fact, it is plausible that areas associated with lower conservation conflicts, as many areas of high ecological integrity, might be targeted by this strategy (Venter et al. 2017). We argue that resource allocation should prioritize ecosystems already known for their multifaceted ecological integrity and integrate, when possible, a variety of biodiversity values (Di Marco et al. 2019). At the same time, conservation strategies should underscore the values and interests of indigenous peoples and local communities while safeguarding their land tenure and respecting their rights. These communities play a key role in conservation (Garnett et al. 2018), and the implementation of conservation measures should duly account for their stewardship both outside and inside protected areas.

5 | Conclusions

Operating with limited time and resources, assessing and monitoring global trends and patterns of conservation and habitat loss is one of the biggest challenges of the CBD (Geldmann et al. 2021). Proposed indicators (CBD/COP/DEC/15/5 2022) provide a limited depiction of what ecological integrity is, representing only a small portion of existing methodologies and failing to fully capture the complexity of this concept. By comparing alternative approaches for the identification of ecological integrity, our findings display the variety of existing methodologies for mapping integrity, revealing the implications of implementing the post-2020 GBF. Our analysis stresses how different measures serve different attributes and scales of ecosystems. Structure-oriented approaches provide a robust measurement of anthropogenic impact, serving as reliable indicators of habitat conservation. However, these approaches are a potential oversimplification of ecosystems' multidimensional nature. On the other hand, composition-oriented approaches provide detailed insights into biodiversity patterns and trends. Nevertheless, these metrics, to be effective, necessitate complex models and depend on

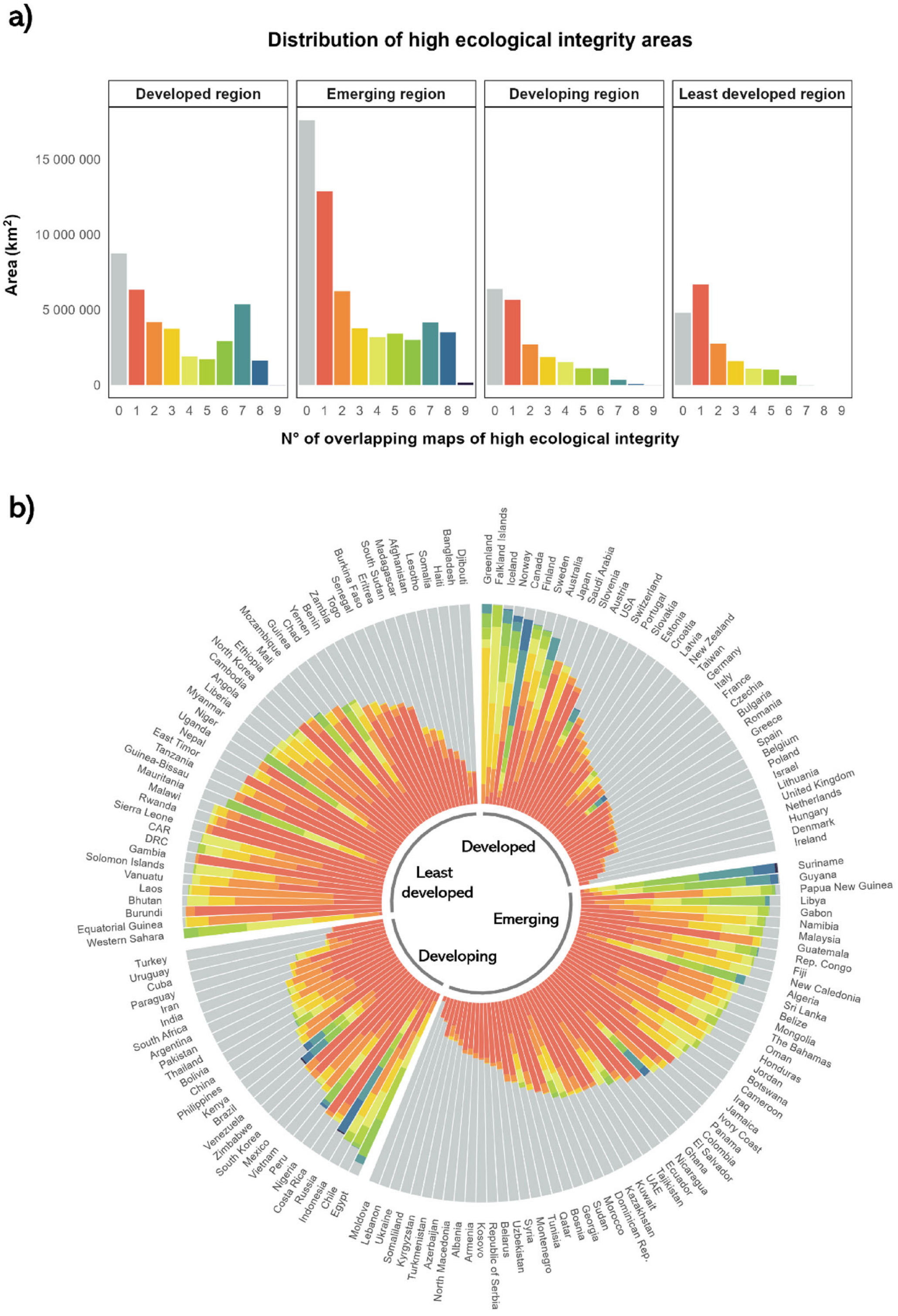


FIGURE 3 | Land area of high ecological integrity according to a selection of nine maps (a) and national-level percentage of area of high ecological integrity (b), with bars ranging from 0% to 100%. Countries are grouped on the basis of their economic category in "developed," "emerging," "developing," and "least developed." Gray areas in the bar plots mean no integrity value according to any of the maps of high ecological integrity. We excluded countries with land area <10,000 km^2 from the figure (n: 85).

the quality and availability of species' occurrence data, potentially leading to incomplete assessments in regions lacking such data (Schmeller et al. 2017). Function-oriented approaches focus on ecosystem services and provide valuable insights into actual ecological processes and services, but achieving their global representation remains a challenge (Nicholson et al. 2021).

Ecological integrity integrates multiple components, but there is currently no explicit indication in the GBF about whether all components must be represented at the same time to meet Target 1. From a practical perspective, most of the existing metrics are presented as proxies of "integrity" in a general sense, even if only focusing on one component of integrity. Several of these metrics are under evaluation as potential indicators for Target 1. Our aim here was to demonstrate that the congruence among various integrity metrics is only partial, and what is referred to as "ecological integrity" does not typically address all aspects of integrity. Diversified approaches to measure ecological integrity result in spatial divergences among maps, with only a negligible percentage of lands (<1%) exhibiting high ecological integrity for all the existing maps. This result emphasizes that choosing one integrity measure over the others carries the inherent risk of underestimating the ecological value of some areas. By contrast, we found that more than two-thirds of areas of high compositional integrity also have high structural integrity. Our study demonstrates that considering the complementarity of alternative approaches has the potential to guide the conservation of different values of ecological integrity. It is also worth highlighting that most metrics of integrity present continuous values (rather than categorical classifications), and it is not always clear whether there are genuine biological reasons to establish a threshold of "high" versus "low" integrity. When clear biological justifications are missing, the identification of "high integrity" areas will likely depend on sociopolitical goals (i.e., selecting a certain percentage coverage of the areas with the highest integrity). Importantly, our findings also suggest that relying on a combination of integrity measures has the potential to guide more effective and equitable conservation paradigms. In fact, our results suggest that industrialized countries bear a heightened responsibility to delineate effective strategies for implementing the post-2020 GBF. At the same time, opting to use a set of integrity maps enables the prioritization of multiple ecological and socioeconomic values while allowing room for flexibility in developing and least developed countries. This flexibility should be used to arrange equitable trade-offs between conservation managers and local stakeholders. The inclusion of ecological integrity within the post-2020 GBF marks a significant milestone toward the conservation of natural ecosystems. Decision-makers and regional managers are now confronted with the task of formulating ambitious strategies that uphold the rights of indigenous peoples and local communities. The concept of ecological integrity is deeply grounded in scientific research at a fine scale (e.g., Carter et al. 2019). Our analysis stresses out that validating global assessments with fine-scale metrics is fundamental to accurately elucidate the actual condition of an ecosystem's structure, composition, and function and the validity of the integrity threshold. However, by carefully interpreting existing measures, current approaches can aid in monitoring and safeguarding ecosystem integrity, whereas more sophisticated indicators are under development.

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Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.